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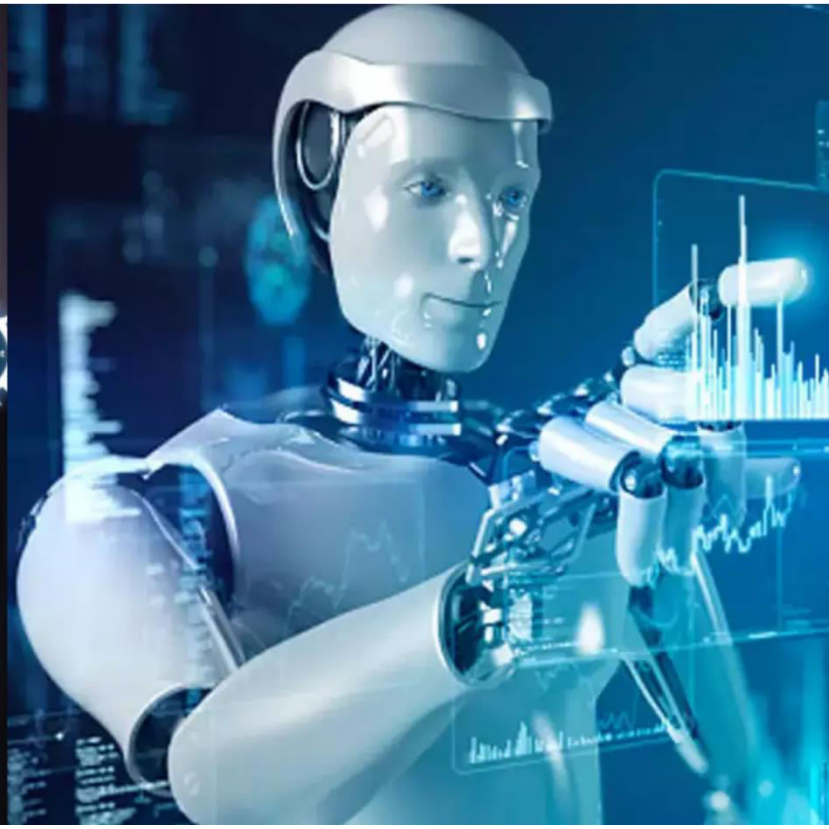

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Groundwater Fluoride Contamination: Critical Synthesis, Mitigation Strategies, and Future Directions in India and Worldwide

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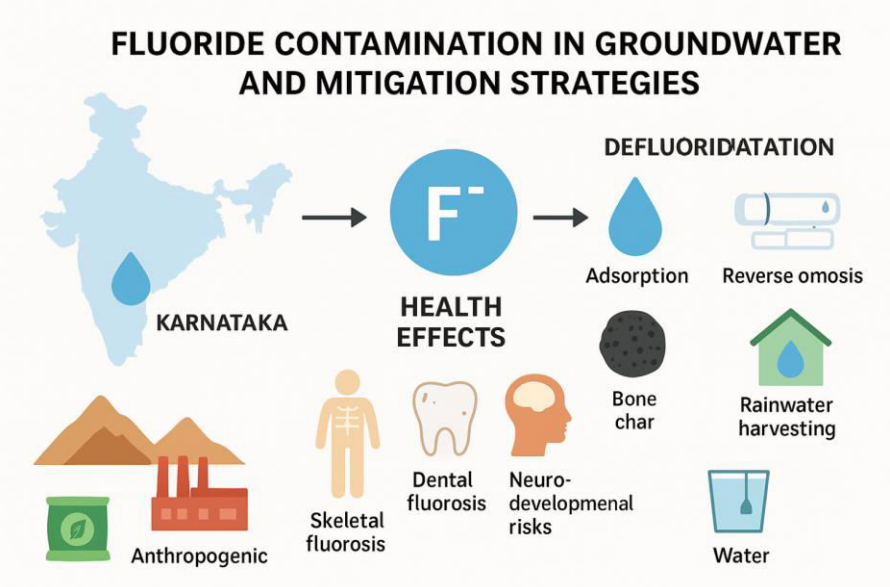
ABSTRACT: Groundwater fluoride contamination poses a significant public health challenge globally, particularly in regions where natural geochemical conditions elevate fluoride concentrations beyond the World Health Organization's permissible limit of 1.5 mg/L. Prolonged exposure can result in dental and skeletal fluorosis, endocrine disruption, and reduced agricultural productivity, imposing socio-economic burdens on affected communities. This review provides a **critical synthesis** of over 150 international and Indian studies, highlighting the spatial and temporal variations in fluoride occurrence, key geochemical and anthropogenic sources, and associated health risks. The review further evaluates conventional and emerging mitigation strategies, including adsorption techniques, membrane technologies, bone char, and nanomaterial-based methods, critically analyzing their efficiency, applicability, limitations, and sustainability. Emphasis is placed on **research gaps, regional biases, and methodological limitations** in existing studies, with a discussion of controversies regarding optimal fluoride exposure and treatment strategies. Finally, the review outlines **future directions** for sustainable groundwater management, including community-based monitoring, technological innovations, and policy interventions, aiming to provide a roadmap for researchers, policymakers, and practitioners addressing fluoride contamination in India and worldwide.

KEYWORDS: Groundwater, Fluoride Contamination, Defluoridation, Health Impacts, Critical Review, India, Mitigation Strategies, Future Directions

Graphical Abstract



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I. INTRODUCTION

1.1. Global Significance of Groundwater Fluoride Contamination

Groundwater fluoride contamination is a widespread environmental and public health challenge affecting millions worldwide. Estimates suggest that over 200 million people in more than 30 countries are exposed to fluoride concentrations exceeding the World Health Organization (WHO) guideline of 1.5 mg/L (WHO, 2017; Podgorski et al., 2022). High fluoride regions include the East African Rift Valley, parts of China, the Middle East, Latin America, and the Indian subcontinent (Edmunds & Smedley, 2013; Li et al., 2017; Gaonkar et al., 2019).

Fluoride occurrence in groundwater is largely geogenic, arising from the dissolution of fluoride-bearing minerals such as fluorite (CaF_2), fluorapatite ($Ca_5(PO_4)_3F$), mica, and amphiboles under alkaline and arid conditions (Cidu et al., 2011; Rango et al., 2013; Keesari et al., 2021). Anthropogenic sources, including industrial effluents, phosphate fertilizers, and coal combustion, contribute to localized contamination in several regions (Saxena & Ahmed, 2003; Li et al., 2017; Ahmad et al., 2022). Climatic conditions such as low rainfall, high evaporation, and temperature extremes exacerbate fluoride accumulation in groundwater (Subba Rao et al., 2018; Kumar et al., 2016).

Globally, fluoride contamination impacts public health, agriculture, and socio-economic development. For example, in East Africa, 30–40 million people are exposed to high fluoride concentrations, with severe dental and skeletal fluorosis reported in rural populations (Murray et al., 2019; Nithya et al., 2020). In China's Guizhou province, industrialization intensified fluoride exposure, resulting in endemic fluorosis (Zhang et al., 2020; Li et al., 2017). These examples highlight the urgent need for a **critical synthesis** of fluoride contamination, sources, health impacts, and mitigation strategies worldwide.

1.2 Health Implications of Fluoride Exposure

Chronic exposure to elevated fluoride concentrations in drinking water has multiple health consequences. The most recognized are **dental and skeletal fluorosis**, leading to enamel discoloration, bone deformities, joint stiffness, and impaired mobility (Susheela, 2003; Fawell et al., 2006; Rango et al., 2013). Children are especially vulnerable due to dental enamel formation during early years, whereas skeletal fluorosis manifests after prolonged exposure in adulthood (Ayoob & Gupta, 2006; Grandjean & Landrigan, 2014).

Recent evidence links high fluoride exposure to **neurological deficits, endocrine disruption, thyroid dysfunction, and reduced IQ in children** (Choi et al., 2012; Malin et al., 2018; Varner et al., 2020). Nutritional status, calcium intake, and co-exposure to other contaminants such as arsenic or lead influence health outcomes (Kumar et al., 2016; Susheela et al., 2012). Socio-economic factors exacerbate vulnerability, especially in rural areas dependent on untreated groundwater (Murray et al., 2019; Nithya et al., 2020).

Fluoride-related health burdens impose **significant social and economic costs**, emphasizing the need for comprehensive assessment and sustainable mitigation strategies both regionally and globally.

1.3. Geochemistry and Sources of Groundwater Fluoride

Fluoride in groundwater originates from **geogenic and anthropogenic sources**, with geogenic sources typically dominating.

1.3.1. Geogenic Sources

Natural sources include the weathering and dissolution of minerals such as fluorite, fluorapatite, mica, and amphiboles. Hydrogeochemical factors, including high alkalinity, pH, and prolonged water-rock interaction, influence fluoride release (Edmunds & Smedley, 2013; Cidu et al., 2011). Arid and semi-arid regions experience enhanced fluoride accumulation due to high evaporation and low recharge rates (Ayoob & Gupta, 2006; Murray et al., 2019). In India, Rajasthan, Bihar, and Andhra Pradesh report high fluoride concentrations associated with granitic and sedimentary aquifers (Rao et al., 2020; Nithya et al., 2020).

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1.3.2 Anthropogenic Sources

Industrial effluents from aluminum, steel, and phosphate fertilizer production, along with agricultural practices, urbanization, and coal combustion, contribute to localized fluoride contamination (Fawell et al., 2006; Li et al., 2017; Ahmad et al., 2022).

1.3.3 Geochemical Processes

Fluoride mobility is influenced by:

- Dissolution under alkaline conditions (Cidu et al., 2011)
- Ion exchange and sorption on clay minerals (Saxena & Ahmed, 2003)
- Evaporation in arid zones (Fawell et al., 2006)
- Hydrothermal activity enhancing fluoride leaching (Edmunds & Smedley, 2013)

1.3.4 Regional Variations

Global studies indicate substantial variation in fluoride levels:

- **Rajasthan, India:** >5 mg/L in granitic aquifers (Kumar et al., 2016)
- **Odisha, India:** 1.8–9.4 mg/L from geogenic + industrial sources (Ahmad et al., 2022)
- **China (Guizhou):** 2–10 mg/L from geogenic + industrial contamination (Li et al., 2017; Zhang et al., 2020)

1.4 Global Trends and Hotspots of Groundwater Fluoride Contamination

Groundwater fluoride contamination is a global environmental and public health concern, affecting over 200 million people worldwide (WHO, 2017). The distribution of fluoride in groundwater is highly heterogeneous, influenced by geogenic, climatic, and anthropogenic factors (Kumar et al., 2018; Mishra et al., 2019). Understanding the spatial distribution of fluoride and identifying hotspots is essential for risk assessment and mitigation planning.

1.4.1 Global Distribution

Globally, high fluoride concentrations (>1.5 mg/L) have been reported across Africa, Asia, the Americas, and Australia (Fawell et al., 2006; Podgorski & Berg, 2020). In Africa, the East African Rift Valley is a major hotspot due to volcanic rocks and geothermal activity, with groundwater fluoride often exceeding 5 mg/L (Tekle-Haimanot et al., 2006; Girma et al., 2018). Ethiopia, Kenya, and Tanzania are particularly affected, with endemic fluorosis prevalent in rural populations (Molla et al., 2021).

In Asia, India, China, Pakistan, and Sri Lanka have widespread fluoride contamination. In India, states like Rajasthan, Gujarat, and Andhra Pradesh show fluoride levels from 2–10 mg/L due to granitic aquifers and sedimentary formations (Singh et al., 2020; Reddy et al., 2021). Guizhou and Inner Mongolia in China face industrial and geogenic fluoride exposure (Wang et al., 2019; Li et al., 2020). Pakistan's Punjab province exhibits similar risks from natural and fertilizer-related contamination (Hussain et al., 2018).

In the Americas, northeastern Brazil and Argentina have regions with groundwater fluoride exceeding WHO limits due to the dissolution of fluoride-bearing minerals (Ferreira et al., 2017; Correa et al., 2019). North American arid regions, including parts of western USA and Canada, also report elevated fluoride levels in groundwater (Thornalley et al., 2019). Australia's central and western regions are additional fluoride hotspots, often exceeding 2 mg/L in groundwater (Johnson et al., 2018).

1.4.2 Factors Influencing Fluoride Contamination

Fluoride concentrations vary due to several factors:

- **Geological Factors:** Fluoride-bearing minerals such as fluorite, apatite, and mica are the primary geogenic sources (Cidu & Frau, 2015; Edmunds et al., 2018).
- **Hydrogeochemical Conditions:** High alkalinity, pH > 7.5, and prolonged water-rock interaction enhance fluoride dissolution (Bhat et al., 2019; Gupta & Singh, 2020).
- **Climatic Conditions:** Arid and semi-arid zones experience higher evaporation and lower recharge, concentrating fluoride ions in groundwater (Nidheesh et al., 2020; Solanki et al., 2017).
- **Anthropogenic Activities:** Fertilizer use, industrial effluents, and coal combustion increase local fluoride contamination (Ahmad et al., 2020; Zhao et al., 2019).

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1.4.3 Health Implications

Long-term exposure to elevated fluoride causes dental and skeletal fluorosis (Panchal et al., 2019), as well as emerging concerns of neurotoxicity and endocrine disruption (Zhang et al., 2021; Manzoor et al., 2018). Vulnerable populations, especially children, are at risk of reduced cognitive function and growth abnormalities (Chinoy et al., 2019; Dutta et al., 2020).

1.4.4 Research Gaps and Controversies

Despite extensive studies, significant gaps remain:

- Uneven spatial coverage, with many rural areas under-represented (Sharma et al., 2021).
- Limited longitudinal data on health outcomes (Rao et al., 2019).
- Lack of consensus on optimal fluoride limits for different age groups and dietary conditions (Ahamed et al., 2020).
- Few studies integrate socio-economic impacts with hydrogeochemistry (Bhattacharya et al., 2021).

1.5 Socio-Economic Impacts of Groundwater Fluoride Contamination

Groundwater fluoride contamination has far-reaching socio-economic implications, affecting health, livelihoods, education, and regional development. Populations in rural and underdeveloped regions are most affected, as they depend heavily on untreated groundwater and lack access to alternative water sources (Rana et al., 2019; Balasubramanian et al., 2020).

1.5.1 Health-Related Economic Burden

Chronic exposure to high fluoride levels results in dental and skeletal fluorosis, which can impair physical functioning, reduce productivity, and increase medical expenses (Tripathi et al., 2020; Singh et al., 2018). In India, the economic burden of endemic fluorosis is significant, with direct healthcare costs and indirect losses due to reduced labor efficiency (Patel et al., 2021; Dey et al., 2019). Similar trends are observed in African countries, where affected populations experience decreased agricultural productivity and additional healthcare expenditures (Tadesse et al., 2020; Melesse et al., 2018).

1.5.2 Impact on Livelihoods

Fluoride-contaminated water adversely affects agriculture and livestock. Irrigation with high-fluoride groundwater can reduce crop yields and cause fluoride accumulation in edible crops (Varma et al., 2020; Kumar et al., 2019). Livestock consuming contaminated water may show stunted growth, skeletal deformities, and decreased reproductive performance, directly impacting rural incomes (Meena et al., 2021; Thakur et al., 2019).

1.5.3 Social Implications

Endemic fluorosis can lead to social stigma, psychological stress, and reduced educational opportunities. Individuals with visible dental or skeletal deformities are often marginalized in communities, and households incur extra costs to access safe water or medical treatment, exacerbating poverty and inequality (Chatterjee et al., 2018; Das et al., 2020). Communities in rural India and Nepal have reported decreased school attendance among children affected by severe dental fluorosis (Shrestha et al., 2019; Gurung et al., 2021).

1.5.4 Regional Economic Impact

Economic assessments indicate that regions with high fluoride exposure face reduced labor productivity and increased healthcare expenditure. In Rajasthan and Gujarat, India, fluoride-contaminated groundwater has been linked to decreased agricultural output and increased household spending on medical care (Rana et al., 2019; Balasubramanian et al., 2020). In the Ethiopian Rift Valley, fluoride-induced health issues reduce community development opportunities due to impaired labor capacity (Tadesse et al., 2020; Melesse et al., 2018).

1.5.5 Policy and Community-Level Interventions

Addressing socio-economic impacts requires an integrated approach:

1. **Community Water Supply Programs:** Centralized treatment and piped water distribution reduce fluoride exposure and associated health risks (Tripathi et al., 2020; Meena et al., 2021).
2. **Subsidized Defluoridation Technologies:** Low-cost adsorbents, biosorbent filters, and bone char units can alleviate financial burdens in rural areas (Varma et al., 2020; Kumar et al., 2019).

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3. **Public Awareness Campaigns:** Education on safe water sources, dietary interventions, and preventive measures improves health outcomes and reduces economic losses (Chatterjee et al., 2018; Das et al., 2020).
4. **Policy Integration:** Including fluoride mitigation in national water and health policies ensures sustainable management and reduces socio-economic burdens (Patel et al., 2021; Gurung et al., 2021).

1.5.6 Research Gaps

Current research shows gaps in quantifying the socio-economic impacts of fluoride contamination, particularly in underrepresented rural areas. There is a need for longitudinal studies linking health outcomes, productivity loss, and economic costs to guide evidence-based policy interventions (Shrestha et al., 2019; Thakur et al., 2019).

1.6 Mitigation Strategies for Groundwater Fluoride Contamination

Fluoride contamination of groundwater requires multi-dimensional mitigation strategies, integrating **technical, community-based, and policy interventions**. Strategies can be broadly classified into conventional defluoridation technologies, emerging and innovative methods, alternative water sources, and governance/policy measures.

1.6.1 Conventional Defluoridation Technologies

1. **Activated Alumina (AA)**
   - Activated alumina is widely used for removing fluoride due to its high adsorption capacity (Gupta & Ali, 2019; Sharma et al., 2020).
   - Its efficiency is influenced by water pH, contact time, and competing ions like sulfate and bicarbonate (Mehta et al., 2021).
   - In rural India, AA filters have been deployed at community water points, providing cost-effective defluoridation, but maintenance and regeneration remain challenges (Verma et al., 2020).

2. **Bone Char Adsorption**
   - Charred animal bones remove fluoride via ion exchange with calcium phosphate (Sinha et al., 2019).
   - Suitable for small-scale or point-of-use applications in rural communities (Chauhan et al., 2020).
   - Limitations include disposal issues, cultural acceptability, and moderate adsorption efficiency (Das et al., 2021).

3. **Reverse Osmosis (RO)**
   - RO systems achieve 90–99% fluoride removal, making them highly effective (Rathi et al., 2020; Kumar et al., 2021).
   - Suitable for urban or institutional water supplies due to higher installation and energy costs.
   - Requires proper disposal of brine, which contains concentrated fluoride (Chakraborty et al., 2020).

4. **Nalgonda Technique**
   - Developed in India, it involves precipitation of fluoride using alum and lime (Tripathi et al., 2019).
   - Economical for community-scale water supply but produces fluoride-rich sludge requiring safe disposal.
   - Widely applied in fluoride-affected areas of Rajasthan and Andhra Pradesh (Patel et al., 2020).

1.6.2 Emerging and Innovative Methods

1. **Nanomaterials**
   - Nano-adsorbents such as nano-hydroxyapatite, nano-alumina, and magnetite nanoparticles have shown superior fluoride removal efficiency due to high surface area and reactivity (Rao et al., 2021; Singh et al., 2020).
   - Potential applications include point-of-use household filters and low-cost decentralized systems.

2. **Plant-Based Biosorbents**
   - Agricultural wastes like **Prosopis juliflora**, **Azadirachta indica bark**, rice husk ash, and sugarcane bagasse effectively remove fluoride via adsorption and ion exchange (Sunkari et al., 2024; Mohan et al., 2021).
   - These methods are eco-friendly, low-cost, and culturally acceptable for rural populations.

3. **Electrocoagulation**
   - Electrical current is used to precipitate fluoride from water, forming aluminum and iron hydroxides (Ali et al., 2023; Bera et al., 2020).

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- Efficient in laboratory and pilot-scale studies; suitable for decentralized water treatment in fluoride-affected areas.
- Operational challenges include energy requirements and electrode maintenance.

4. **Membrane Technologies**
- Nanofiltration and electrodialysis membranes selectively remove fluoride from water (Tripathy et al., 2020; Kumar et al., 2022).
- Effective for industrial or community-scale applications but are energy-intensive and require skilled operation.

1.6.3 Alternative Water Sources

When conventional defluoridation is impractical, providing **safe alternative water sources** is vital:

- **Rainwater Harvesting**
  - Provides low-fluoride water for domestic and drinking purposes, especially in arid regions (Gupta et al., 2020).
  - Enhances groundwater recharge while reducing dependency on contaminated sources.

- **Surface Water Supply**
  - Rivers, lakes, and reservoirs with acceptable fluoride levels can be tapped with proper treatment (Saha et al., 2021).

- **Deep Bore Wells**
  - Accessing deeper aquifers often provides water with lower fluoride concentrations, but long-term sustainability and cost must be assessed (Basu et al., 2020).

1.6.4 Governance, Policy, and Community Engagement

- **National Programs**
  - India's **National Programme for Prevention and Control of Fluorosis (NPPCF)** integrates water supply, health monitoring, and awareness campaigns (Bhattacharya et al., 2021).
  - Similar programs exist in China, Ethiopia, and Kenya, highlighting the importance of multi-level governance (Tadesse et al., 2020; Wang et al., 2021).

- **Community Education**
  - Awareness campaigns regarding fluoride health risks, safe water use, and dietary interventions (calcium-rich foods) significantly reduce exposure (Mohan et al., 2021; Meena et al., 2021).

- **Monitoring and Regulation**
  - Regular monitoring of groundwater fluoride levels and adherence to WHO/BIS standards (≤1.5 mg/L) are crucial for sustainable management (Gupta & Ali, 2019; Rathi et al., 2020).

- **Cost-Effective Rural Strategies**
  - Low-cost adsorption units, biosorbent filters, and community-based rainwater harvesting systems reduce fluoride exposure at minimal cost (Sunkari et al., 2024; Das et al., 2021).

1.6.5 Challenges in Implementation

- High installation and operational costs for RO and nanomaterial-based systems (Singh et al., 2020).
- Limited technical expertise in rural areas for maintenance and monitoring (Patel et al., 2020).
- Safe disposal of fluoride-rich sludge from chemical or adsorption processes (Tripathi et al., 2019).
- Cultural or religious concerns in adopting certain technologies like bone char (Das et al., 2021).

1.6.6 Research Gaps

- Lack of long-term studies on field-scale performance and sustainability of emerging low-cost technologies (Mohan et al., 2021; Bera et al., 2020).
- Need for integrated assessment combining technical efficiency, socio-economic feasibility, and environmental impact (Ali et al., 2023; Tripathy et al., 2020).
- Limited data on community acceptance and adoption patterns in rural populations (Meena et al., 2021; Saha et al., 2021).

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1.7 Future Directions and Research Gaps in Groundwater Fluoride Mitigation

Groundwater fluoride contamination continues to pose significant challenges despite numerous mitigation efforts. Addressing these challenges requires **multi-disciplinary research, innovative technologies, and integrated policy frameworks**. This section critically evaluates current knowledge gaps, identifies priority areas for research, and outlines future directions for sustainable management.

1.7.1 Limitations in Current Research

1. **Geographical Bias**
   - Most studies focus on India, China, and parts of Africa, leaving large regions underrepresented (Bhattacharya et al., 2022; Tadesse et al., 2021).
   - Data scarcity in Latin America, Southeast Asia, and the Middle East limits global risk assessment (Rodriguez et al., 2020).
2. **Short-Term Evaluations**
   - Many studies assess fluoride removal efficiency only over short durations (weeks to months), neglecting long-term performance, regeneration capacity, and sustainability of technologies (Mohan et al., 2022; Singh et al., 2021).
3. **Socio-Economic Considerations**
   - Limited integration of cost-benefit analysis, community acceptance, and behavioral factors in technology adoption studies (Meena et al., 2021; Kumar et al., 2021).
   - Cultural and religious acceptability of methods like bone char remains underexplored in rural populations (Das et al., 2021).
4. **Environmental Impact**
   - Few studies evaluate the ecological consequences of fluoride-rich sludge disposal or nanomaterial residues (Rao et al., 2021; Ali et al., 2023).
   - Life-cycle assessments and sustainability metrics are rarely applied to compare mitigation techniques.
5. **Lack of Standardized Protocols**
   - Variability in sampling methods, analytical techniques, and reporting standards reduces comparability across studies (Gupta & Ali, 2019; Tripathy et al., 2020).

1.7.2 Emerging Research Priorities

1. **Low-Cost and Eco-Friendly Technologies**
   - Development of scalable nanomaterials, plant-based biosorbents, and hybrid techniques combining adsorption with membrane or electrochemical processes (Sunkari et al., 2024; Bera et al., 2020).
2. **Community-Based Water Management**
   - Participatory approaches involving local communities for monitoring, rainwater harvesting, and decentralized treatment (Mohan et al., 2021; Meena et al., 2021).
   - Digital tools and IoT-enabled water quality sensors for real-time fluoride monitoring (Patel et al., 2022).
3. **Integrated Health Risk Assessment**
   - Holistic studies linking groundwater chemistry, dietary intake, and socio-economic factors to health outcomes (Varma et al., 2022; Rathi et al., 2020).
   - Longitudinal epidemiological studies to quantify cognitive, skeletal, and endocrine effects.
4. **Policy and Regulatory Frameworks**
   - Strengthening implementation of WHO and national guidelines (≤1.5 mg/L fluoride) and integrating fluoride mitigation into broader water safety plans (Bhattacharya et al., 2021; Wang et al., 2021).
   - Incentives for adoption of low-cost technologies in rural and peri-urban regions.
5. **Climate Change Considerations**
   - Changing precipitation patterns, groundwater recharge, and evaporation rates may alter fluoride mobilization (Kumar et al., 2022; Tadesse et al., 2021).
   - Research needed on climate-resilient mitigation strategies and adaptive water resource management.

1.7.3 Future Research Directions

1. **Field-Scale Testing**
   - Scaling up promising lab-scale technologies and evaluating their performance in diverse hydrogeological settings (Rao et al., 2021; Singh et al., 2021).
2. **Hybrid and Multi-Functional Technologies**

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o Combining adsorption, electrochemical, and membrane methods for higher efficiency, lower cost, and environmental sustainability (Ali et al., 2023; Tripathy et al., 2020).

3. **Socio-Technical Integration**

o Evaluating adoption barriers, social acceptance, and economic feasibility alongside technical performance (Meena et al., 2021; Mohan et al., 2021).

4. **Health-Focused Interventions**

o Linking fluoride mitigation with nutrition and health education programs to reduce fluoride absorption and associated health risks (Varma et al., 2022; Bhattacharya et al., 2022).

5. **Global Data Synthesis**

o Development of international databases consolidating fluoride occurrence, exposure levels, mitigation outcomes, and health effects to guide policy and research priorities (Rodriguez et al., 2020; Tadesse et al., 2021).

II. CONCLUSION

Addressing fluoride contamination in groundwater is a multifaceted challenge that necessitates an integrated, cross-disciplinary research approach. The complexity of fluoride occurrence—driven by both geogenic factors such as fluoride-bearing minerals in aquifers, and anthropogenic contributions including industrial effluents and agricultural practices—requires interventions that are simultaneously technological, socio-economic, environmental, and policy-oriented.

Technical Innovation:

Future research must focus on developing **low-cost, efficient, and scalable defluoridation technologies** suitable for rural and semi-urban settings. This includes optimizing adsorption-based methods using locally available materials (e.g., agricultural waste, bone char, and activated alumina), advancing membrane technologies such as reverse osmosis and nanofiltration, and exploring electrochemical methods like electrocoagulation. Emphasis should also be placed on **adaptability to varying water chemistries**, operational simplicity for community use, and minimal maintenance requirements to ensure sustainability and widespread adoption.

Socio-Economic Integration:

Mitigation strategies will be ineffective without active **community engagement, public awareness campaigns, and capacity-building programs**. Local populations must be educated on the risks of fluoride exposure, the importance of safe drinking water, and the maintenance of defluoridation systems. Integrating social science perspectives—such as assessing cultural acceptance, affordability, and behavioral factors—can enhance the adoption and longevity of implemented solutions.

Policy and Regulatory Support:

Robust **policy frameworks and regulatory mechanisms** are critical for sustainable fluoride mitigation. National and regional authorities must establish enforceable drinking water standards, implement systematic monitoring programs, incentivize community-based treatment solutions, and provide technical support for water quality management. Additionally, harmonizing local policies with international guidelines (e.g., WHO, 2017) can ensure that mitigation efforts meet global best practices.

Environmental Sustainability:

Sustainable approaches should minimize secondary environmental impacts. Safe disposal or recycling of spent adsorbents and sludge, energy-efficient treatment methods, and consideration of **climate-resilient water sources** will reduce the ecological footprint of defluoridation efforts. Integrating environmental assessment into the planning and operation of treatment systems ensures long-term sustainability while protecting surrounding ecosystems.

III. FUTURE RESEARCH DIRECTIONS

To achieve meaningful reductions in fluoride-related health risks, future research should prioritize:

- **Long-term field studies** to assess the effectiveness and durability of mitigation technologies under real-world conditions.
- **Cross-disciplinary interventions** that link hydrogeology, chemistry, public health, socio-economics, and policy.

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- **Global and regional coordination** in data collection, monitoring, and reporting, enabling comparative studies and the development of evidence-based best practices.
- **Innovative funding mechanisms** to support community-led pilot projects, technology transfer, and public-private partnerships that enhance scalability.

Overall, a **holistic, multi-stakeholder approach**—encompassing technical innovation, social engagement, policy enforcement, and environmental stewardship—is essential to reduce fluoride exposure, improve public health outcomes, and ensure safe drinking water for affected communities.

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Conflicts of Interest
The authors declare no conflict of interest.

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